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Mathematical model of dynamic behaviour of a diesel engine in propulsion system

SUMMARY

The subject of the analysis described in the paper is the method of determining the torque developed by the engine in simulation investigation of dynamic processes of the propulsion system. The analysis encompasses the identification of engine model structure and the initial identification of the values of model parameters, which have been determined basing on the obtained results of engine investigation on test stand. The measured and model curves of engine speed and torque versus time showed good comformity.

INTRODUCTION

Each propulsion system consists of three main functional sub-assemblies: engine, power transmission equipment and propeller. In the simplest case a propulsion system consists only of an engine and propeller (Fig. 1). The system is influenced purposely by setting certain parameters on the engine and propeller. Environment conditions also influence the system.

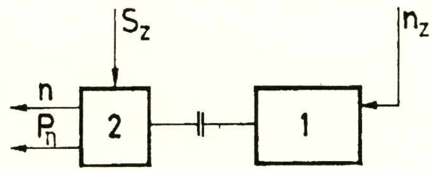

Fig. 1. Propulsion system block diagram
1 - Engine, 2 - Propeller; n_z , n - set and real engine speed values, S_z - propeller setting, P_n - propulsion force.

Among the set values the most important is the set engine speed and the setting of propeller torque change.

The transient process is produced by changing settings in steady work conditions of the system. The basic role in the mathematical description of such a process is played by the equation of the rotary motion of shaft line :

$$2\pi J\frac{dn}{dt} = m_e - m_h \qquad (1)$$

where: m_e - effective torque of engine (torque developed by the engine in transient state),
m_h - propeller moment,
n - engine speed (rpm),
J - rotational mass moment of inertia of the system reduced to the axis of engine crankshaft.

The subject of the analysis described in the present paper is the method of determining the moment developed by the engine in simulation investigations of dynamic processes of the system.

In order to ensure the stable work of an engine and the required speed regulation quality in all work conditions of the propulsion system, engines are provided with speed governors. The governors determine the setting of injection pump in function of the set and measured rpm values. Further in this paper the speed governor is treated as a separate sub - system. Its mathematical model is a separate vast problem and will not be presented here.

PROPOSED MODEL

A diesel engine is a multidimensional dynamic system both in steady and transient states. In investigations of dynamic processes of propulsion systems there is a need to apply a model of the engine,in which the injection pump setting h and engine speed n represent the input values and the torque measured at the crankshaft flange m_c is

setting h and engine speed n represent the input values and the torque measured at crankshaft flange m_c is the output quantity. Different models answer this need. A large number of references is devoted to this problem [1, 2 - 9, 12 - 19]. Important features of such models are their complexity and extensiveness determining the possibilities of their application in simulation investigations.
The presented model describes turbocharged engines. The injection pump is treated in it as a separate element. Detailed numerical data given below refer to M-401 engine (rating : 810 kW at 27 1/s and turbocharger compression 2.0).

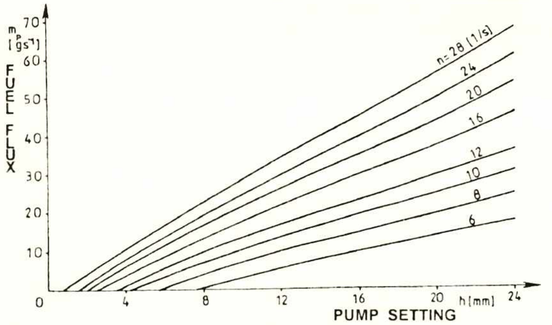

Fig. 2. Static characteristics of injection pump

The input quantity of injection pump are: its setting h and engine speed n. On the other hand the fuel flux to cylinders mp is the output quantity value. In the model of propulsion unit the injection pump can be treated as an inertialess element. The assumption in mathematical description is justified by physical experiments [5, 19] . Thus the static characteristics $m_p = m_p$ (h, n) of the pump can be accepted as its mathematical model.
The characteristics have been determined for M-401 engine basing on laboratory test results of four pumps [11]. A polynomial function approximating test results has been determined for points from m_p, h, n space by means of least square method (Fig. 2). The Chebyshev polynomial, which is considering the physical phenomena occuring in the pump as well as meeting the assumed accuracy condition, is a third degree polynomial :

$$m_p = \sum_{i=1}^{10} K_w(i) h^p n^q \qquad (2)$$

In further consideration concerning the construction of the mathematical model of the propulsion unit the notion of engine should be understood as all the elements and engine sub - systems as well as the processes followed by them apart from the injection pump and speed governor. Fuel flux to cylinders and speed are the input quantity for the so understood engine while torque compared with the load torque in the rotary motion of shaft line is the output quantity. In steady states this is the torque acting on the crankshaft flange. It is denoted by m_u and named steady state effective torque. The static characteristics of engine is the basis for the construction of the mathematical model of the engine.

The engine is an inertia element. Energy accumulation in the turbocharging system as well as thermal energy accumulation in cylinder walls and in the cooling medium should be foreseen in the engine model with torque as output quantity. Thus it is proposed to treat the engine as a specific inertia element. Its mathematical model consists of :

- a function describing the effective steady state torque depending on the fuel flux to cylinders and on speed: $m_u = m_u$ (m_p, n);
- the division of m_u quantity into three components: the instantaneous component, the first delayed com ponent appearing mainly due to the energy accumulation in the supercharging system, the second delayed component representing the thermal energy accumula tion in cylinder walls as well as in the supercharging system;
- differential equations describing the delayed components and the summation of all the three components. The model block diagram is shown in Fig. 4.

A form of the static characteristics of the engine can be determined basing on characteristics given by engine makers: effective power, effective torque or mean effective pressure depending on speed and specific fuel consumption. In the presented case the characteristics have been received by approximation using Chebyshev polynomial in m_u, m_p, n space of the measuring points (Fig. 3) [11]. The polynomial meeting the requirements of accuracy is a polynomial of the fourth degree:

$$m_u = \sum_{i=1}^{15} K_m(i) m_p^p n^q \qquad (3)$$

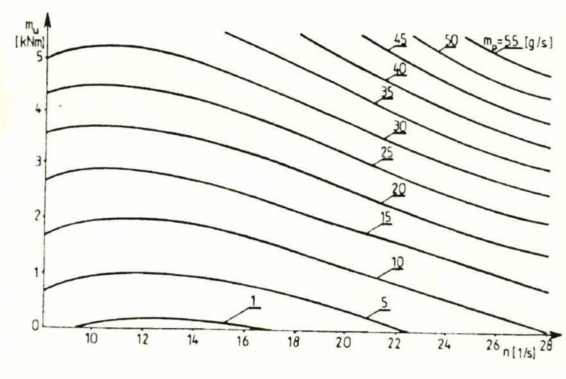

Fig. 3. Static characteristics of M-401 engine

Exponents in function of index "i" occuring in the equations acquire the following values:

i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 ,15
p = 0, 0, 1, 0, 1, 2, 0, 1, 2, 3, 0, 1, 2, 3 , 4
q = 0, 1, 0, 2, 1, 0, 3, 2, 1, 0, 4, 3, 2, 1, 0.

It results from the investigations of engine dynamic behaviour described in the literature [4, 17, 3, 6] as well as from the author's own research that the delayed effective torque components occur mainly due to supercharging.

Let us introduce the coefficient of mean effective pressure increase of the supercharged engine comparing it with a hypothetical unsuperchaged engine, both working in rated conditions:

$$K_c = \frac{p_e - p_{en}}{p_e} \tag{4}$$

It is proposed to present the division of effective torque and description of its components in the following form:

The first delayed component will be described by a linear differential equation of the first degree with amplification factor $K_c\ K_{c1}$ and time-constant T_1

$$T_1 \dot{m}_{e1} + m_{e1} = K_c K_{c1} m_u \tag{5}$$

and the delayed second component by a linear differential equation of the second degree with amplification factor K_c ($1 - K_{c1}$), time-constant T_2 and damping coefficient ζ :

$$T_2^2 \ddot{m}_{e2} + T_2 \zeta \dot{m}_{e2} + m_{e2} = K_c (1 - K_{c1}) m_u \tag{6}$$

where K_{c1} - coefficient of division of delayed components.

The immediate component is represented by the following formula:

$$m_{eu} = (1 - K_c) m_u \tag{7}$$

Thus the effective torque in transient states m_e will be the sum:

$$m_e = m_{eu} + m_{e1} + m_{e2} \tag{8}$$

In the first approximation it is proposed to calculate the time constants T_1 and T_2 occuring in (5) and (6) as well as the damping coefficient ζ from the following formulae [10, 11]:

$$T_1 = \frac{2\pi J n_{Tn}}{M_{Tn}} \tag{9}$$

$$T_2 = \frac{\dfrac{W_{sc} R_{sc}}{4 F_{sc}}}{\dfrac{3}{\sqrt{\alpha_g R_{sc} + 1}}} \tag{10}$$

$$\zeta = \frac{2\left(\dfrac{3}{\alpha_g R_{sc} + 1} + 1\right)}{\sqrt{\dfrac{3}{\alpha_g R_{sc} + 1}}} \tag{11}$$

where: J, W_{sc} , R_{sc} , F_{sc} are material and construction constants:

J - moment of inertia of turbocharger rotor ,

W_{sc} - thermal capacity of cylinder walls participating in the heat transmission from the working medium to the cooling medium,

R_{sc} - mean heat transmission resistance in walls from the working medium to the cooling medium,

F_{sc} - internal surface of cylinder walls when the piston is in area its lowest dead position; and n_{Tn} , M_{Tn}, α_g , - represent parameters characterizing the work of engine under rated load:

n_{Tn} - turbocharger speed,

M_T - torque developed by the turbocharger,

α_g - mean value of surface heat conductance coefficient from the working medium to the cylinder walls, for one cycle.

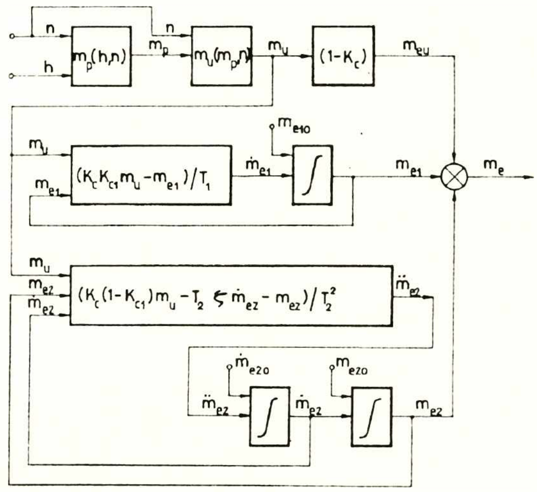

Fig. 4. Block diagram of the model

The presented analysis encompasses the identification of engine model structure and the initial identification of the values of model parameters. In order to bring the model precisely enough to real engine appropriate investigations of the dynamic behaviour of the engine have been conducted on test stand. The model parameters have been determined basing on the obtained results.

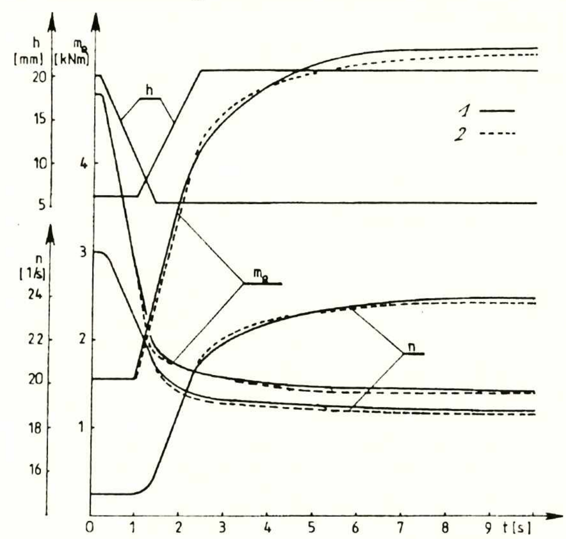

Fig. 5. Comparison of measured and model curves of engine speed n and torque m_e versus time (1 - measurements, 2 - model.)

The test stand was provided with a water brake. Its output shaft was connected with a mass rotating together with the shaft. The inertia moment of this mass was approximately 10 times higher than the inertia moment of the rotating parts of the engine. Among other things changes of the following quantities were recorded in function of time: injection pump settings h, engine speed n and torque in the shaft between engine and brake, recognized as m_e. Linear changes of h in function of time with constant settings of the brake and with interlocked speed governor have been applied in the tests in order to cause the transition from one steady state to another. Values of K_c, K_{cl}, T_1, T_2, ζ constants have been determined using "adjusting method" [20] basing on registered curves of h, n, m_e, and curves obtained in simulation investigations. Fig. 5 shows n, m_e curves in function of time obtained from measurements and from the simulation model with the process induced by the change of injection pump setting h. Values of engine model constants are given in Table 1.

Tab.1

SYMBOL	DIMENSION	VALUE	SYMBOL	DIMENSION	VALUE h>0	VALUE h<0
K	1	0,55	T_1	s	0,95	0,11
			T_2	s	2,10	0,85
K	1	0,73	ζ	1	2,01	2,10

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